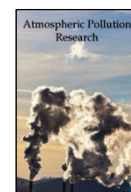


# Atmospheric Pollution Research

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## Ambient particulate pollution during Chinese Spring Festival in urban Lanzhou, Northwestern China

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### ABSTRACT

The effect of firework displays on ambient particulate pollution in a typical valley city in Northwestern China was evaluated based on high temporal resolution atmospheric particle size distribution (10–10 000 nm) data and particle mass concentrations in different sizes obtained during 25<sup>th</sup> January – 24<sup>th</sup> February, 2013. Firework displays have significant impact on particle number concentrations in accumulation mode (100–1 000 nm), especially in 200–500 nm, as well as PM<sub>1</sub> mass concentrations. The hourly mean number concentration in 200–500 nm and PM<sub>1</sub> mass concentration during the peak hour of firework displays were 11 800.2±2 548.0 cm<sup>-3</sup> and 214.1±31.2 µg m<sup>-3</sup>, which are approximately 6 times and 2 times of that before the festival, respectively, with a maximum 10–min mean number concentration in size range 100–1 000 nm reaching 3.8×10<sup>4</sup> cm<sup>-3</sup> on the New Year's Eve (00:10 BT 10<sup>th</sup> February, 2013). It was estimated that local emissions and firework displays contributed 74.6% and 37.0%, respectively, to the number concentration of particles less than 1 000 nm. On short-time scale, the contribution of firework displays on local particulate pollution is obvious and should not be ignored, especially on fine particulate pollution.

**Keywords:** Particulate pollution, fireworks, Lanzhou, Spring Festival



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### 1. Introduction

With the development of economy, more attention is paid to short-term air quality degradation events and their negative impact on human health. Firework set off can cause notable short-term particulate and gaseous pollution during festivals all over the world, especially particulate air pollution, which poses a serious threat to human health. During Chinese Spring Festival, generally occurs in January or February, one of the most attractive activities is the nationwide firework displays. In particular, the most intensive firework events occur on the Chinese New Year's Eve in most cities and rural areas, which can lead to a slight and dramatic increase in gaseous pollutants (Ravindra et al., 2003) and atmospheric particulate matter concentrations (Jin et al., 2007; Zhao et al., 2011) in a short time period, respectively. The short-term air quality degradation caused by fireworks may result in serious health hazards (Ravindra et al., 2001; van Kamp et al., 2006) and a reduction in visibility for hours (Vecchi et al., 2008).

Considering the adverse impacts of fireworks on air quality and human health, since the 1990's some researchers studied the atmospheric particle size distributions and mass concentrations during firework displays and some important results were obtained at different places over the world (Wehner et al., 2000; Drewnick et al., 2006; Rissler et al., 2006; Moreno et al., 2007; Barman et al., 2008; Vecchi et al., 2008; Croteau et al., 2010; Joly et al., 2010; Singh et al., 2010; Thakur et al., 2010; Agrawal et al., 2011).

Wehner et al. (2000) indicated that the most affected particles by fireworks was in the accumulation mode range, i.e. D<sub>p</sub>>100 nm. Vecchi et al. (2008) observed an increase of particle number concentrations up to 6.7 times in 1 h in the size of 500<D<sub>p</sub><1 000 nm during a firework episode. Few studies have been carried out describing the particle concentrations and their size distributions during Chinese Spring Festival (Hong et al., 2003; Li et al., 2006; Jin et al., 2007; Wang et al., 2007; Li et al., 2008; Zhang et al., 2008; Zhang et al., 2010; Wang et al., 2011; Zhao et al., 2012), with most of them focused on economically developed regions in central or eastern China and developed coastal cities. For example, Zhang et al. (2010) studied particle number concentration and their size distribution properties by measuring particles in 10–1 000 nm using a Wide-range Particle Spectrometer at 20 m above the ground level during firework events in Shanghai. Their results indicated a clear contribution of firework activities to number concentration of accumulation mode particles and PM<sub>1</sub> mass concentration. Li et al. (2006), Jin et al. (2007), and Zhang et al. (2008) explored changes of particulate pollution and their impacts on air quality before and after the official firework prohibition in Beijing and showed the significant increase of fine particulate concentration by firework displays in urban area. Wang et al. (2007) analyzed chemical compositions of atmospheric aerosols during the Lantern Festival in Beijing in 2006 and showed that chemical compositions, such as Ba, K, Sr, SO<sub>4</sub><sup>2-</sup> and NO<sub>3</sub><sup>-</sup>, during bonfire night were five times higher than those during other nights. Until now, there is limited amount of literature describing

the effects of firework displays on atmospheric particle concentration in cities in Northwestern China. Wang et al. (2008) found a greater short-term contribution of firework displays to near ground pollutant concentrations than other pollution sources by studying the spatial-temporal characteristics of particle mass concentrations during Spring Festival in urban and suburban Xi'an in Northwestern China. Shi et al. (2011) investigated the influence of firework events on perchlorate in  $PM_{10}$  and  $PM_{10-100}$  in Lanzhou and Yuzhong during Chinese Spring Festival and found the levels of perchlorate during firework displays was 5.8–25.2 times higher than that during the period of no or limited firework displays. There have been no relevant reports on the effects of firework displays on submicron particle size distributions in northwestern China. In this study high resolution particle size distributions in 10–10 000 nm were analyzed to better understand the effect of short-term firework displays on particle concentrations in different size ranges and changes in aerosol particle size distribution properties during firework events.

The objective of this study is to investigate the effect of short-period firework events on urban air quality, especially particle concentrations and their size distributions using in situ observations, and quantify the contribution of firework emissions to urban particle concentrations in different size ranges.

## 2. Methods

### 2.1. Sampling site

Lanzhou (36.05°N, 103.88°E), located at the intersection of Qinghai–Tibet Plateau, the Inner Mongolian Plateau and the Loess Plateau, has an average elevation of 1 520 m and is surrounded by mountains and hills rising to 500–600 m. It is the capital of the Gansu province, with an area of 13 thousand square kilometers and a population of 2.58 million. The area has a semi-dry climate, with an annual average temperature of 8.9 °C, and an annual average precipitation of 331 mm. Figure 1 shows the location of Lanzhou and the sampling site. There are two major roads with traffic volume of more than 2 000 cars per hour near the sampling site, one of which is 20 m from the sampling site (Donggang West Road in Figure 1), and the other is about 300 m west of the sampling site (Tianshui Road in Figure 1). The sampling site was on the roof of a 32 m high research building of the Cold and Arid Regions Environmental and Engineering Research Institute

(CAREEI), Chinese Academy of Sciences, located in the eastern part of the Lanzhou urban area. The main activities in its surroundings are residential and commercial. A study by Imhof et al. (2005) indicated that at 30 m above ground the background concentration was attained. So, our instrument captured the particle concentrations and size distributions representing Lanzhou urban environment.

### 2.2. Measurement

Continuous particle size distributions (10–10 000 nm) were measured using scanning mobility particle sizer (SMPS model 3936, TSI, USA) and aerodynamic particle sizer (APS model 3321, TSI, USA) during 25<sup>th</sup> January to 24<sup>th</sup> February, 2013. The SMPS and APS measure the size distribution of aerosols in the size range 10–1 000 nm and 500–10 000 nm, respectively. The SMPS measures the particle size distribution using an electrical mobility detection technique, which uses a bipolar charger in the Electrostatic Classifier to charge the particles to a known charge distribution. The particles are then classified according to their traverse ability in an electrical field, and the number of particles in a specified size range is counted by Condensation Particle Counter (CPC). The APS is a time-of-flight spectrometer that measures the velocity of particles in an accelerating airflow through a nozzle. Aerosol is drawn into the inlet and is immediately split into a sample flow (1 L/min) through the inner nozzle, and a sheath flow (4 L/min) through the outer nozzle. In the present study, in order to combine particle size distributions measured with the two instruments, particle sizes from SMPS and APS were binned into 107 and 37 channels in the size range 10–800 nm and 800–10 000 nm with a time resolution of 5 min per scan, respectively. Furthermore, the mobility diameters measured by SMPS were converted into aerodynamic diameters measured by APS. The fundamental equation relating aerodynamic diameter  $d_a$  to mobility diameter  $d_m$  is:

$$d_a = d_m \left( \frac{\rho_p}{\chi \rho_0} \right)^{\frac{1}{2}} \quad (1)$$

where  $\rho_p$  is the particle density,  $\rho_0$  is the reference density  $1 \text{ g cm}^{-3}$ , and  $\chi$  is a dynamic shape factor. In this study  $\chi$  is taken as 1, and  $\rho_p$  is calculated using integral particle volume concentrations in 10–2 500 nm and the corresponding  $PM_{2.5}$  mass concentration.

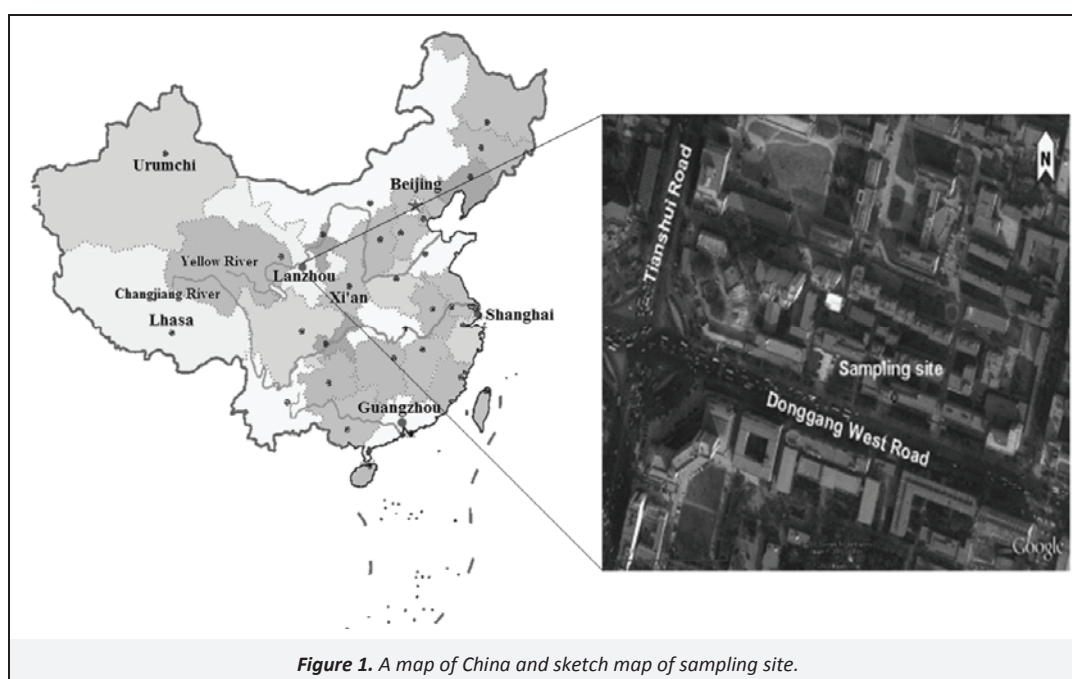


Figure 1. A map of China and sketch map of sampling site.

During the experiment, the impactor of SMPS, and the inner and outer nozzle of the APS were cleaned every day and every two weeks, respectively. Meanwhile, the sample and sheath flow rates of SMPS and APS were examined periodically with a bubble flow meter to insure the good performance of the instruments. As part of the study, the SMPS's mobility and the APS's time-of-flight responses were calibrated using monodisperse aerosols prior to their deployment in the field. In addition, invalid data were eliminated based on the percentage of events 1–4 of every APS data sample and data samples with event 2 accounting for more than 75% were retained.

In order to explore the effect of fireworks on particle size distribution properties, the hourly mean particle number size distributions (PNSD) during 12:00 9<sup>th</sup> – 12:00 10<sup>th</sup> February 2013 (Chinese New Year's Eve) were fitted using multivariate logarithm normal distribution. The formula of lognormal distribution is as follows:

$$\frac{dN}{d \log D_p} = \sum_{i=1}^n \frac{N_i}{\sqrt{2\pi} \log \sigma_i} \exp \left( -\frac{(\log D_p - \log \bar{D}_{p,i})^2}{2(\log \sigma_i)^2} \right) \quad (2)$$

where,  $N_i$ ,  $\bar{D}_{p,i}$ , and  $\sigma_i$  are the total number concentration, the number mode diameter and the standard deviation of modal  $i$ , respectively.  $n$  is the number of individual log-normal modes that characterize the particle size distribution. The fit criterion was chosen to satisfy a goodness of fit test at 5% significance level with minimum number of modes (Shrestha et al., 2010), and no modes are therefore allowed to have a spacing less than  $d \log D_p < 0.15$ , which roughly corresponds to a ratio of  $D_p$ 's  $> 1.4$  (Tunved et al., 2003).

Ten-minute meteorological data, including air temperature, relative humidity and wind speed and direction, were obtained with an automatic meteorological station co-located with the sampling site. In addition, continuous on-line  $PM_{10}$ ,  $PM_{2.5}$  and  $PM_{10}$  concentrations were measured using a laser spectrometer DustTrak™ DRX Aerosol Monitor by TSI Inc. (TSI Model 8533), which recorded PM concentrations on an 1 min basis. The spectrometer data were corrected based on gravimetric measurements by medium-volume samplers Tianhong-150 with  $PM_{2.5}$  and  $PM_{10}$  inlets. Beijing time (BT) (=UTC+8) is used in this paper. As there was no episode of very high particulate concentrations during 12:00 25<sup>th</sup> January – 12:00 8<sup>th</sup> February before the Chinese New Year (CNY) (10<sup>th</sup> February 2013), the variations of particle concentrations and their size distributions during CNY (12:00 9<sup>th</sup> – 12:00 10<sup>th</sup> February) were compared with that before the CNY to better understand the effect of firework displays on urban air quality. In addition, evolution of particle number concentrations in different size bins during 12:00 10<sup>th</sup> – 12:00 24<sup>th</sup> February after the CNY were also analyzed to investigate the hazardous situation after the intensive firework displays.

### 3. Results and Discussion

#### 3.1. Particle concentrations affected by firework displays

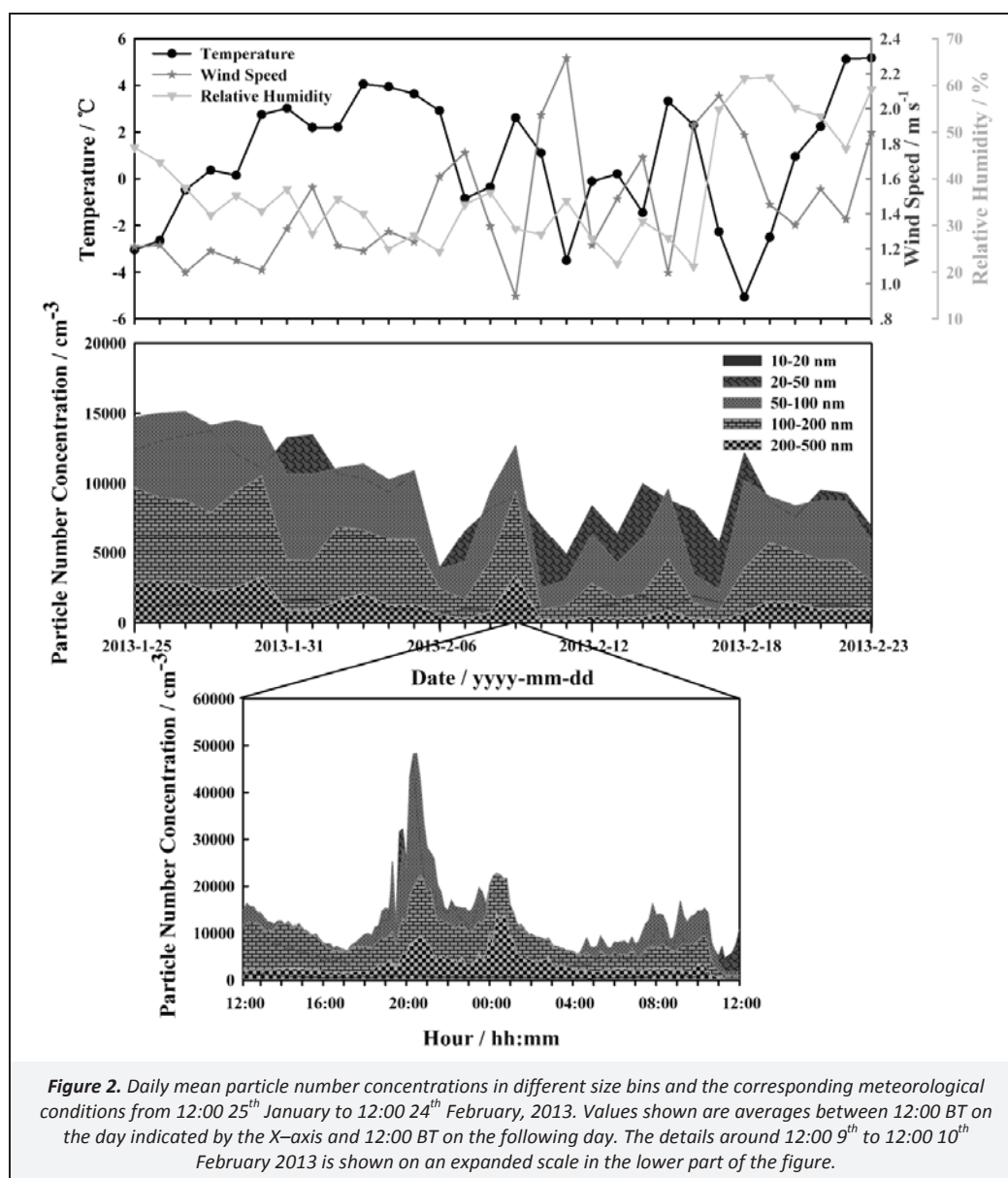
A large amount of firework displays and sparkles were set off primarily since soon after the dinner time (around 19:00 BT) on Chinese New Year's Eve (9<sup>th</sup> February, 2013) in the whole city, with the highest point around midnight (00:00–01:00 BT) on 10<sup>th</sup> February, 2013. The mean  $PM_{2.5}$  concentration was  $140 \mu g m^{-3}$  during 12:00 9<sup>th</sup> February – 12:00 10<sup>th</sup> February 2013, which exceeded the national Grade I ( $35 \mu g m^{-3}$ ) and II ( $75 \mu g m^{-3}$ ) standard for daily mean  $PM_{2.5}$  concentrations by 300% and 87%, respectively. The results from Barman et al. (2008) and Thakur et al. (2010) also indicated several times higher pollutant concentrations compared to a typical winter day value due to great firework displays on Deepawali in India. In order to better understand the

effect of firework displays on urban particulate pollution in different size ranges, particles in the size range 10–10 000 nm are divided into 7 size bins, i.e. 10–20 nm (nuclei mode), 20–50 nm and 50–100 nm (Aitken mode), 100–200 nm, 200–500 nm and 500–1 000 nm (accumulation mode), and 1 000–10 000 nm (coarse mode) following Zhang et al. (2010). It is seen from Figure 2 that  $N_{50-100 \text{ nm}}$  and  $N_{100-500 \text{ nm}}$  have local maxima during 12:00 9<sup>th</sup> – 12:00 10<sup>th</sup> February and they decreased quickly after due to the relatively high wind speed. The residence time of particles from firework displays in the atmosphere maybe shorter than one day. The relatively high particle number concentrations before CNY were mainly due to the stagnant weather condition dominant in winter in the studied area (Figure 2). The detailed feature around the intensive firework display period was shown in the bottom of Figure 2. Particle number concentrations in size ranges of 100–200 nm and 200–500 nm increased sharply during 20:00–21:00 on 9<sup>th</sup> February and 00:00–01:00 on 10<sup>th</sup> February, especially in the size range 200–500 nm during 00:00–01:00 on 10<sup>th</sup> February, 2013. While the significant increase of  $N_{20-50 \text{ nm}}$  and  $N_{50-100 \text{ nm}}$  at 19:00 on 9<sup>th</sup> February were probably caused by local activities such as people driving out for dinner with families and friends to celebrate the festival and the cooking emissions from nearby residential home, the sharp increase of  $N_{100-500 \text{ nm}}$  during 00:00–01:00 were mainly attributed to firework displays due to few other activities and relatively low wind speed. Many previous studies (Wehner et al., 2000; Drewnick et al., 2006; Agus et al., 2008; Vecchi et al., 2008; Zhang et al., 2010) have indicated the dominance of accumulation mode particles during firework activities, which are consistent with our study. These results indicate that firework activities affected more obviously on particles in small accumulation mode (100–500 nm) than in other modes.

To better understand the effect of firework displays on urban air quality and examine the hazardous situation after the event, the evolution of 10-min mean particle number and mass concentrations in different size ranges before, on and after CNY are shown in Figure 3. Particle number concentrations in 10–20 nm were higher around midday than at other times, especially under relatively clean conditions after the CNY, which may be related to the relatively high solar radiation at noon (Liu et al., 2008). Particle number concentrations in 20–50 nm, 50–100 nm, 100–200 nm, 200–500 nm,  $PM_1$  and  $PM_{1-2.5}$  concentrations have peaks around 20:00 on 9<sup>th</sup> February, which was related to the combined effects of firework displays and local activities. During 00:00–01:00 on 10<sup>th</sup> February, a period mainly affected by firework displays, the particle number concentrations in 100–500 nm,  $PM_1$ ,  $PM_{1-2.5}$  and  $PM_{2.5-10}$  concentrations were much higher than that before and after the CNY. Drewnick et al. (2006) observed peak of submicron aerosol concentrations about 20 min after intensive firework displays with total mass concentrations higher than  $600 \mu g m^{-3}$ , and Khaparde et al. (2012) also suggested noticeable increase in  $PM_{10}$  when the burning of fireworks was maximum in Nagpur during Diwali in India. The relatively lower  $N_{50-500 \text{ nm}}$ ,  $PM_1$  and  $PM_{1-2.5}$  concentrations after CNY were related to the relatively high wind speed accompanied by the passage of a cold front indicated by the drop of temperature by more than 5 °C in 24 hrs (Figure 2).

Meteorological conditions have significant effect on particle number and mass concentrations in different size ranges. A summary of the correlations of particle number and mass concentrations in different size ranges with meteorological variables are given in Table 1.  $N_{10-20 \text{ nm}}$  was positively and negatively correlated with air temperature and relative humidity, respectively, indicating that high temperature and dry air may favor new particle formation by nucleation process (Liu et al., 2008). Particle numbers in other size ranges,  $PM_1$  and  $PM_{1-2.5}$  were negatively correlated with air temperature and wind speed, and positively correlated with relative humidity, which indicate that increased wind speed and deeper atmospheric mixing height related to higher air temperature are favorable for the dispersion and dilution of those particles.





**Table 1.** Correlation of particle number and mass concentrations in different size ranges with meteorological variables

	Meteorological Variables		
	Air Temperature	Relative Humidity	Wind Speed
$N_{10-20 \text{ nm}}$	0.07 <sup>a</sup>	-0.08 <sup>a</sup>	0.07 <sup>a</sup>
$N_{20-50 \text{ nm}}$	-0.02	0.05	-0.07 <sup>a</sup>
$N_{50-100 \text{ nm}}$	-0.09 <sup>a</sup>	0.15 <sup>a</sup>	-0.32 <sup>a</sup>
$N_{100-200 \text{ nm}}$	0.05	0.07 <sup>a</sup>	-0.39 <sup>a</sup>
$N_{200-500 \text{ nm}}$	0.06 <sup>a</sup>	0.06 <sup>a</sup>	-0.35 <sup>a</sup>
$N_{500-1\,000 \text{ nm}}$	-0.03	0.34 <sup>a</sup>	-0.27 <sup>a</sup>
$N_{1\,000-10\,000 \text{ nm}}$	-0.27 <sup>a</sup>	0.38 <sup>a</sup>	-0.13 <sup>a</sup>
$PM_{10}$	-0.03	0.14 <sup>a</sup>	-0.33 <sup>a</sup>
$PM_{1-2.5}$	-0.11 <sup>a</sup>	0.17 <sup>a</sup>	-0.24 <sup>a</sup>
$PM_{2.5-10}$	0.16 <sup>a</sup>	-0.45 <sup>a</sup>	0.24 <sup>a</sup>

<sup>a</sup> Numbers are significant at 0.001 level.

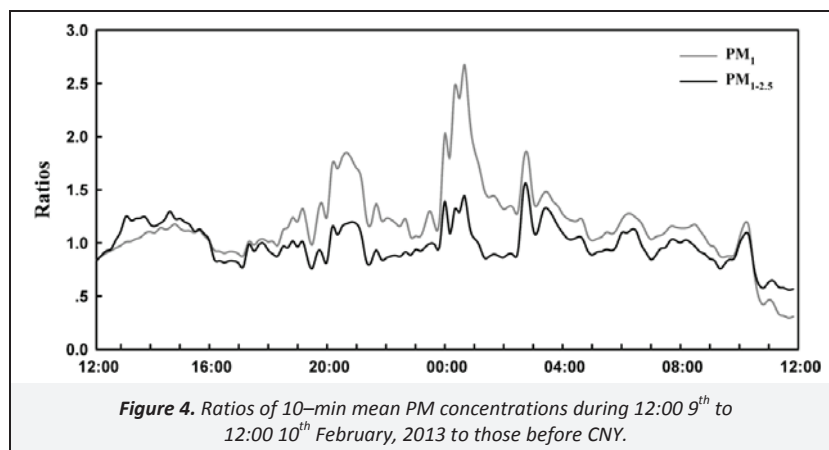
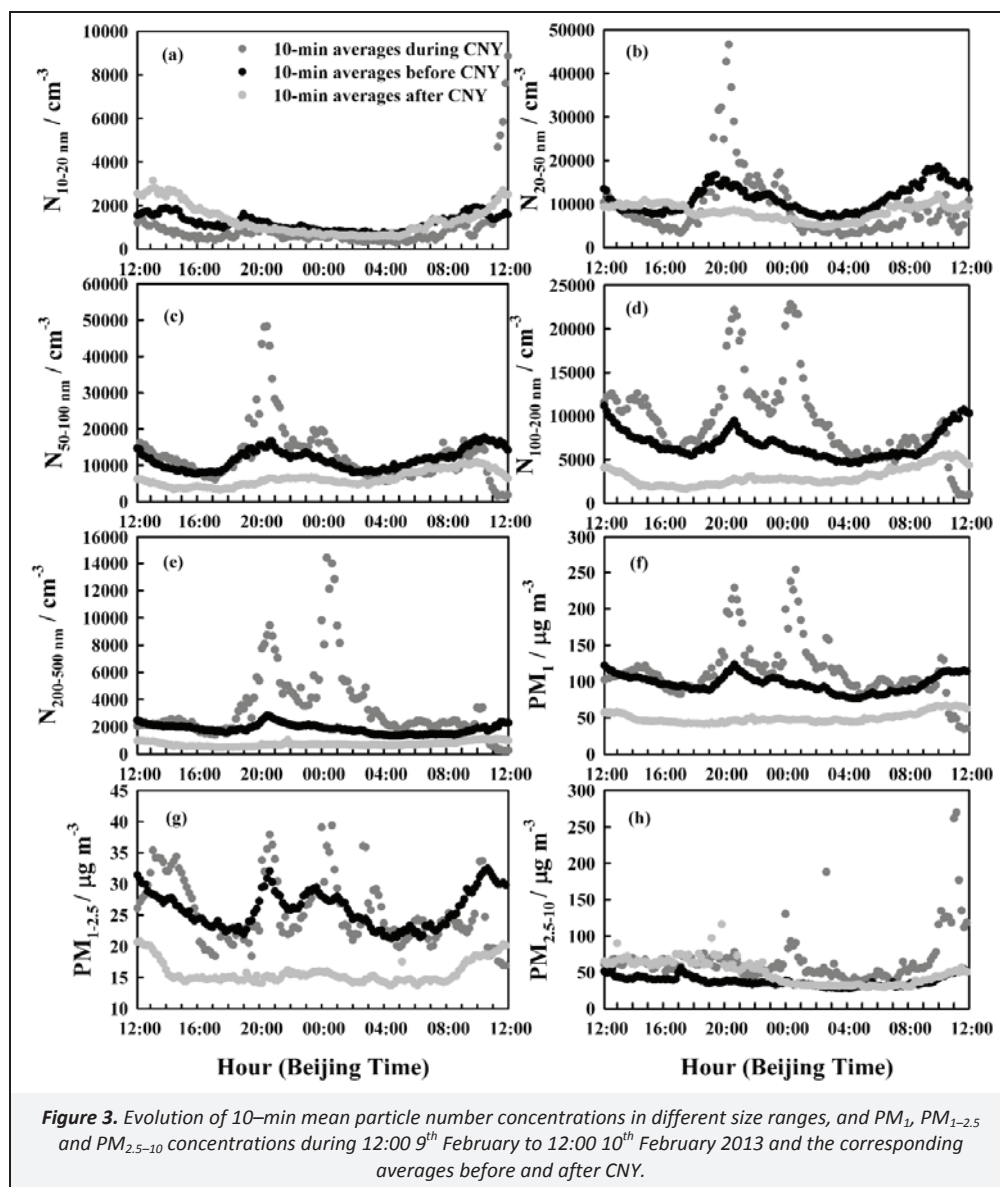
The hourly mean particle number and mass concentrations in different size bins and the corresponding meteorological conditions for the period 20:00–21:00 9<sup>th</sup> February, 00:00–01:00 10<sup>th</sup> February and the corresponding hours before CNY were

compared in Table 2 to study the influence of firework displays on particle concentration and size distributions. As presented in Table 2, particle number and mass concentrations in nearly all size ranges during 20:00–21:00 9<sup>th</sup> February and 00:00–01:00 10<sup>th</sup> February 2013 were higher than those before CNY, especially for particle numbers in size range 100–1 000 nm, and  $PM_{10}$  mass concentration. Wehner et al. (2000) observed the maximum number concentration in accumulation mode after midnight which was approximately one order of magnitude higher than that the night before and after the event, and found the total submicron mass concentration (3–800 nm) reached its maximum, approximately  $235 \mu\text{g m}^{-3}$  after midnight. In our study, the hourly mean  $N_{200-500 \text{ nm}}$  and  $PM_{10}$  mass concentration during 00:00–01:00 on 10<sup>th</sup> February were  $11\,800.2 \pm 2\,548.0 \text{ cm}^{-3}$  and  $214.1 \pm 31.2 \mu\text{g m}^{-3}$ , respectively, which were almost 6 times and 2 times of the corresponding hourly averages before CNY. The maximum 10-min averaged number concentration in size range 100–1 000 nm reached  $3.8 \times 10^4 \text{ cm}^{-3}$  during the peak firework period (00:10 BT on 10<sup>th</sup> February), which accounted 61% of the total number concentration in the size range of 10–10 000 nm. The above analysis indicate that firework displays contributed significantly to particle numbers in 100–1 000 nm, especially particles in 200–500 nm, and  $PM_{10}$  mass concentration, which is consistent with the results from Zhang et al. (2010). During 20:00–

21:00 9<sup>th</sup> February, the hourly averaged number concentration in 50–100 nm was  $40\,850.4 \pm 8\,086.6\text{ cm}^{-3}$ , which was about 3 times of that before CNY. It will be shown later that the elevated  $N_{50-100\text{ nm}}$  was related to local activities.

Ratios of 10-min mean PM mass concentrations during 12:00 9<sup>th</sup> and 12:00 10<sup>th</sup> February to those before CNY are presented in Figure 4 to understand the contribution of firework displays to

particle mass concentrations in different size ranges.  $\text{PM}_{10}$  increased more obviously than  $\text{PM}_{2.5}$ , with  $\text{PM}_{10}$  increased by nearly 2.7 times during 00:00–01:00 10<sup>th</sup> February, 2013. The fraction of  $\text{PM}_{10}$  in  $\text{PM}_{10}$  during 00:00–01:00 on 10<sup>th</sup> February was much higher than that before the CNY. The increase of  $\text{PM}_{2.5}$  fraction in  $\text{PM}_{10}$  was not obvious, indicating the significant contribution of firework displays to  $\text{PM}_{10}$  concentration.



**Table 2.** Hourly mean particle number and mass concentrations in different size bins and the corresponding meteorological conditions for the period of 20:00–21:00 9<sup>th</sup> February and 00:00–01:00 10<sup>th</sup> February and before CNY

Items	Unit	20:00–21:00		00:00–01:00	
		9 <sup>th</sup> February, 2013	Before CNY	10 <sup>th</sup> February, 2013	Before CNY
N <sub>10–20 nm</sub>	cm <sup>-3</sup>	873.3±107.2	1 164.9±94.3	608.3±83.7	797.5±31.0
N <sub>20–50 nm</sub>	cm <sup>-3</sup>	32 739.0±11 124.4	14 369.4±624.5	6 947.7±2 569.2	9 243.3±337.4
N <sub>50–100 nm</sub>	cm <sup>-3</sup>	40 850.4±8 086.6	15 646.5±743.7	15 587.7±2 418.8	10 694.0±525.7
N <sub>100–200 nm</sub>	cm <sup>-3</sup>	20 202.3±1 664.8	8 765.7±496.1	21 142.5±2 579.3	6 088.1±121.8
N <sub>200–500 nm</sub>	cm <sup>-3</sup>	8 385.5±685.8	2 651.3±138.5	11 800.2±2 548.0	1 859.4±22.7
N <sub>500–1 000 nm</sub>	cm <sup>-3</sup>	514.0±44.6	132.9±4.5	664.0±97.3	104.6±2.4
N <sub>1 000–10 000 nm</sub>	cm <sup>-3</sup>	28.6±3.2	9.5±0.2	33.7±3.9	9.6±0.2
PM <sub>1</sub>	µg m <sup>-3</sup>	206.5±14.2	117.1±4.1	214.1±31.2	96.0±1.0
PM <sub>1–2.5</sub>	µg m <sup>-3</sup>	34.9±2.1	30.2±1.2	33.8±3.8	27.6±0.3
PM <sub>2.5–10</sub>	µg m <sup>-3</sup>	67.3±7.7	37.7±0.9	81.1±11.4	34.6±1.8
Air Temperature	°C	5.6	4.1	1.2	0.1
Relative Humidity	%	25.2	28.4	29.7	36.2
Wind Speed	m s <sup>-1</sup>	1.1	1.1	1.1	1.3

### 3.2. Particle size distributions

Although the particle samplers were on the roof of a 32-m high research building, considering the valley-shaped topography, the effect of local emissions such as vertical diffusion of emissions from motor vehicles and horizontal transport of elevated power plant emissions on particle number size distributions cannot be neglected before New Year's Eve, while marginal effect of local emissions maybe present after New Year's Eve due to the long Chinese New Year's Holiday. As shown in Figure 5, particle concentrations before the New Year's Eve (black dashed and black dotted lines) were much higher than that during the New Year's holidays (gray dashed and gray dotted lines). The mean PNSDs before New Year's Eve were unimodal with peaks around 50–70 nm, which were affected by local emissions, while that after the New Year's Eve represent PNSDs with marginal effect from local emissions. The PNSD between 20:00 and 21:00 on 16<sup>th</sup> February peaked at about 20–30 nm, with the lowest particle number concentrations in other size ranges as compared to other days. In addition, the number concentrations for particles larger than 20 nm averaged for 20:00–21:00 on 17<sup>th</sup> February are much lower than other days. The differences of the 16<sup>th</sup> and 17<sup>th</sup> February data from other days may be attributed to meteorological conditions. It can be seen from Figure 6 that the wind speed and relative humidity averaged for 20:00–21:00 16<sup>th</sup> February are the highest and the lowest among the five days, respectively. An investigation of the correlations between particle number concentrations in different size ranges and meteorological variables indicate a negative and a positive correlation of N<sub>>20 nm</sub> with wind speed and relative humidity, respectively (Table 1), which may be due to the favor of nucleation mode particle growth under relatively high relative humidity (Yu et al., 2005) and the favor of accumulation mode particle dispersion under higher wind speed conditions. Comparing the mean PNSDs before New Year's Eve with those after, we can found that local emissions had obvious effect on particles larger than 30 nm, especially around 60 nm. A rough estimation by calculating the relative difference of N<sub>10–1 000 nm</sub> before (20:00–21:00 26<sup>th</sup> January and 2<sup>th</sup> February, 00:00–01:00 27<sup>th</sup> January and 3<sup>th</sup> February) and after (20:00–21:00 16<sup>th</sup> and 23<sup>th</sup> February, 00:00–01:00 17<sup>th</sup> and 24<sup>th</sup> February) the New Year's Eve indicates that 74.6% of particles less than 1 000 nm could be attributed to local emissions. The number size distribution averaged between 20:00 and 21:00 on 9<sup>th</sup> February (solid line in Figure 5a) had clear signature from local emissions, with a peak around 60 nm, probably caused by people driving out for dinner with families and friends to celebrate the festival (Wehner et al., 2000) or the cooking emissions from nearby residential home. The most interesting feature, however, is the maximum in the hourly

mean number concentrations around 190 nm during 00:00–01:00 10<sup>th</sup> February, the period with the most intensive firework displays. A rough estimation by computing the relative difference of N<sub>10–1 000 nm</sub> during (00:00–01:00 10<sup>th</sup> February) and before New Year's Eve indicates that firework displays led to 37.0% increase of particles less than 1 000 nm, which is comparable to the results of Wehner et al. (2000). The above analysis indicate that firework displays and local emissions mainly affect particles in accumulation mode (~190 nm) and Aitken mode (~60 nm), respectively, and the increase of particles in accumulation mode (~190 nm) due to firework displays during 00:00–01:00 10<sup>th</sup> February are around 3 times higher than that due to local emissions, agreeing with Vecchi et al. (2008) who found a significant increase in accumulation mode particles during firework displays. An even more impressive picture of the firework-affected aerosols can be seen in Figure 7. It is clear that particles in the size range 200–600 nm increased greatly during 00:00–01:00 10<sup>th</sup> February, with the maximum increase of 14 times.

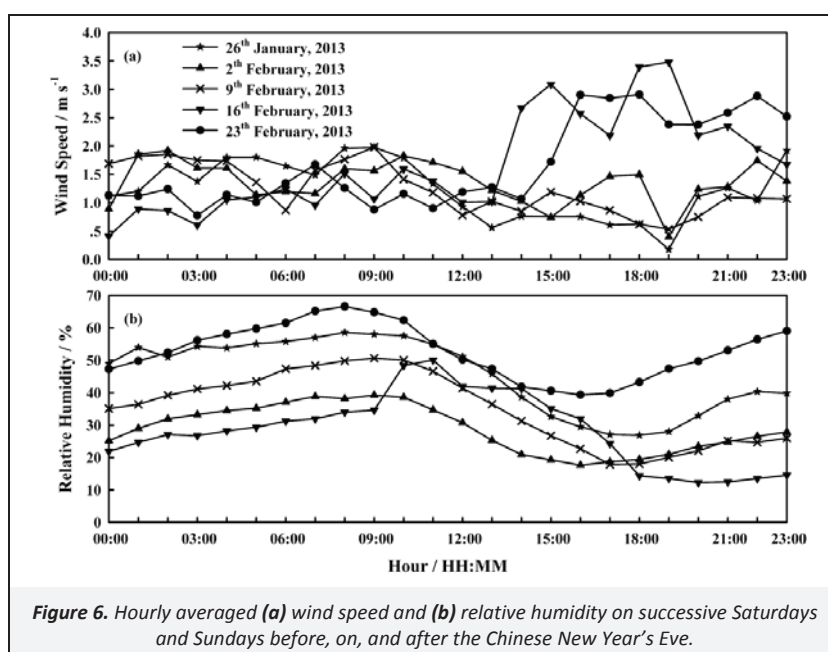
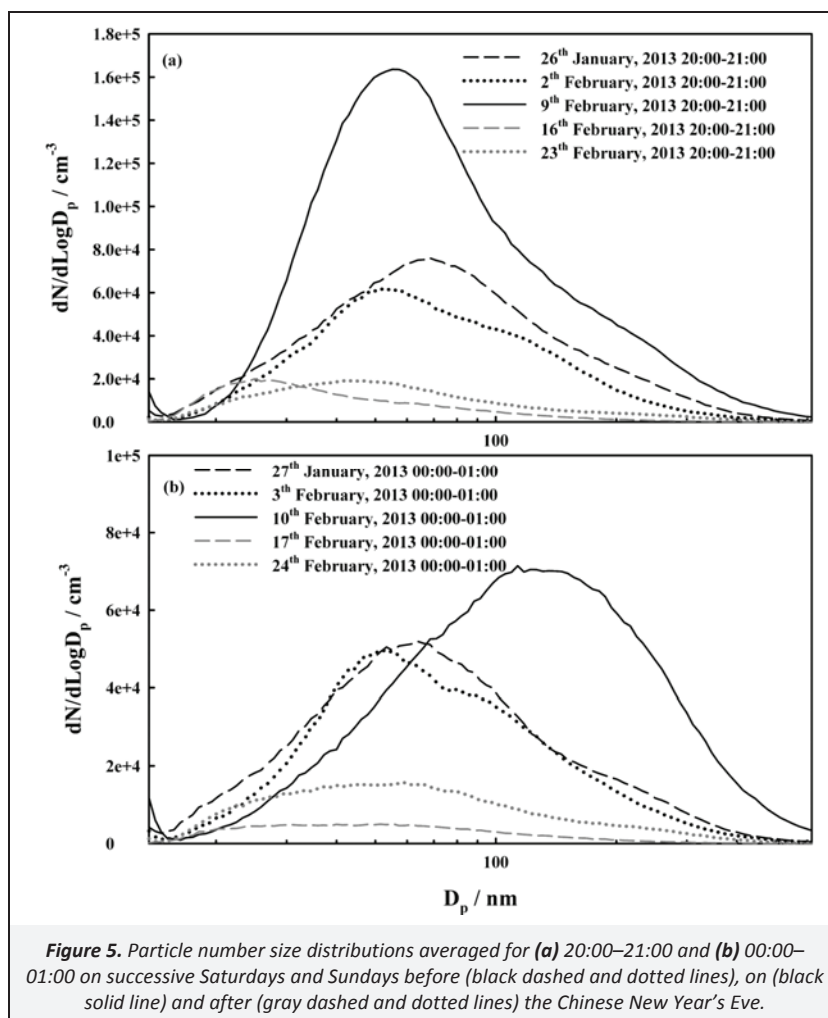
Hourly particle number size distributions during 12:00 9<sup>th</sup> – 12:00 10<sup>th</sup> February 2013 were fitted using multivariate logarithm normal distribution, and the number mode diameter (NMD) is shown in Figure 8. There is a significant increase of number mode diameter and the corresponding number concentration during peak firework displays, which lasted for at least three hours. The NMDs were 51.3 nm and 126.8 nm, respectively, during 20:00–21:00 9<sup>th</sup> February, and the number concentration of the smaller mode was relatively higher, indicating the impact of local activities such as motor vehicles and cooking emissions (Ondracek et al., 2011; Hirsikko et al., 2012). The NMD of the mode with the highest number concentration was 188.9 nm during 00:00–01:00 10<sup>th</sup> February, which was almost the largest NMD during 12:00 9<sup>th</sup> to 12:00 10<sup>th</sup> February. These results indicate that the firework activities had a clear contribution to particle size distributions, especially accumulation mode particles, while normal local emissions affect mainly particles in Aitken mode.

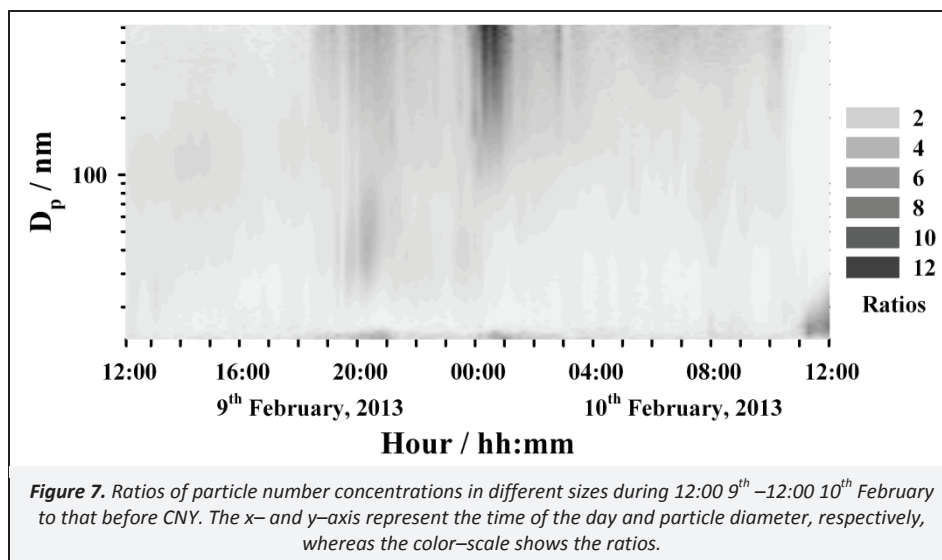
### 4. Conclusions

Firework displays have significant impact on particle number concentrations and size distributions in accumulation mode (100–1 000 nm), especially in 200–500 nm, as well as PM<sub>1</sub> concentrations. The hourly mean number concentration in 200–500 nm and the PM<sub>1</sub> concentration during the peak firework display were 11 800.0±2 458.0 cm<sup>-3</sup> and 214.1±31.2 µg m<sup>-3</sup>, respectively, in our study, which were approximately 6 times and 2 times of the corresponding values before the Chinese New Year. The maximum 10-min mean number concentration in size range 100–1 000 nm

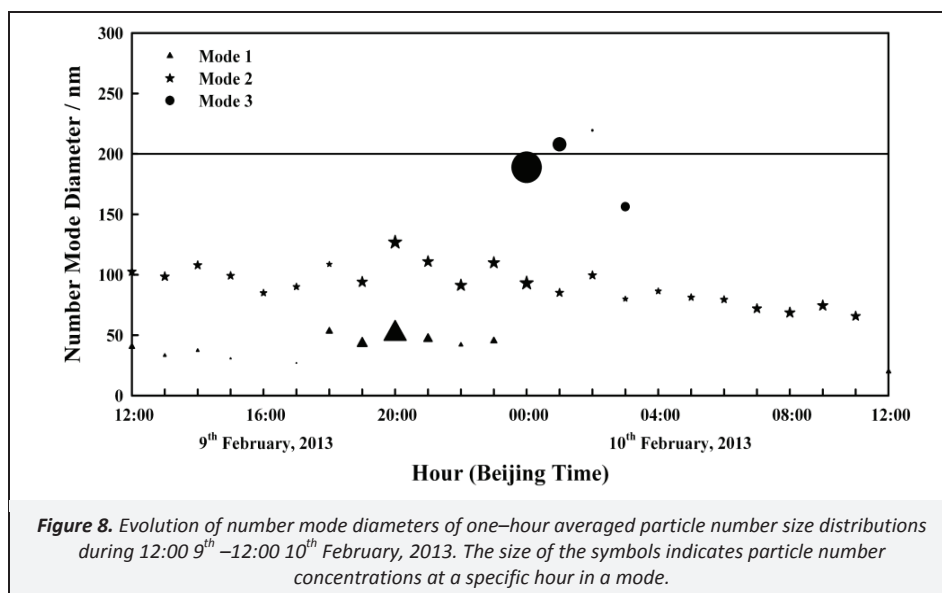
reached  $3.8 \times 10^4 \text{ cm}^{-3}$  on the Chinese New Year's day (00:10 BT on 10<sup>th</sup> February, 2013). The number mean diameter and the corresponding number concentration increased obviously during firework displays. During the peak hour of firework displays (00:00–01:00 10<sup>th</sup> February), the number mode diameter with the highest particle number concentration was 188.9 nm, which was

almost the largest number mode diameter during 12:00 9<sup>th</sup> to 12:00 10<sup>th</sup> February. A rough estimation indicate that local emissions contribute about 74.6% of particle numbers less than 1 000 nm, while the short-term firework displays contribute 37.0% increase in the number concentration of particles less than 1 000 nm.





**Figure 7.** Ratios of particle number concentrations in different sizes during 12:00 9<sup>th</sup>–12:00 10<sup>th</sup> February to that before CNY. The x- and y-axis represent the time of the day and particle diameter, respectively, whereas the color-scale shows the ratios.



**Figure 8.** Evolution of number mode diameters of one-hour averaged particle number size distributions during 12:00 9<sup>th</sup>–12:00 10<sup>th</sup> February, 2013. The size of the symbols indicates particle number concentrations at a specific hour in a mode.

The results from our study indicate that short-term firework displays have obvious effect on fine particulate pollution, and the duration and the extent of its effect on urban air quality depend on various factors such as meteorological conditions during and after the event. The residence time of particles resulted from firework displays is shorter than 1 day in our study due to the good dispersion condition following the passage of a cloud front after the event. Some restrictive measures may be needed under adverse meteorological conditions to improve urban air quality and alleviate fine particulate pollution during Chinese New Year. As indicated by Prakash et al. (2013), relatively high particle concentrations during Diwali were attributed to the burning of fireworks and the adverse meteorological conditions, i.e., low wind speeds and low mixing-layer heights. In this study, due to the lack of mixing height data we were unable to quantify the contribution of meteorological conditions on urban particle concentrations. Further studies are needed to quantitatively evaluate the contribution of different processes.

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